



# Characterization of particles from a marine engine operating at low loads



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## HIGHLIGHTS

- Measurements of particle emissions from low sulfur marine fuels.
- Measurements conducted on a test-bed engine operating at low engine loads.
- Nanoparticles ( $D_p < 50$  nm) were the dominating fraction of total particle number.
- Particle formation is not only related to the sulfur content of the fuel.

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## ABSTRACT

Particle emissions from a marine diesel engine operating at low loads with four different fuels were characterized with respect to particle number (PN) and particle mass (PM), size distribution, volatility and chemical composition. The four different fuels used were Swedish Environmental class 1 (MK1) and class 3 diesel (MK3), heavy fuel oil (HFO, 0.12 wt% S) and marine diesel oil (MDO, 0.52 wt% S). The measurements were performed for a marine diesel engine in a test-bed engine lab and the particle emissions were measured with an Engine Exhaust Particle Sizer and a Dust Monitor, giving the number concentrations in the size range of 5.6–560 nm and 300 nm to 20  $\mu\text{m}$ , respectively. To quantify the amount of solid particles a thermodenuder was used. Additionally, filter samples were taken for gravimetric, black carbon (BC) and elemental analysis. The particle emissions showed a bimodal size distribution by number and the number concentrations were dominated by nanoparticles (diameter ( $D_p$ ) < 50 nm). The nanoparticles measured were both primary and secondary particles, depending on fuel and engine load, while the particles with  $D_p > 50$  nm generally were solid primary particles. Combustion of HFO resulted in the highest PN and PM concentrations. Emission factors (EFs) for PM and PN for both the total particle emissions and the fraction of primary, solid particles are presented for different fuels and loads. EFs for nitrogen oxides ( $\text{NO}_x$ ), BC and some elements (Ca, Fe, V, Ni, Zn) are presented as well. This study contributes to understanding particle emissions from potential future fuels as well as emissions in ports and coastal areas where lower engine loads are common.

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## 1. Introduction

Shipping is the one of the most fuel efficient means of transportation of goods and resources, but at the same time a source of air pollution to consider (Corbett, 2003). Given that around 70% of emissions from ship operations are emitted within 400 km from land, ship operations can be seen as a significant source of air pollution in coastal areas (Corbett et al., 2007). In light of up-

coming regulation of allowed sulfur (S) content in marine fuels, both within sulfur emission control areas ( $\text{SO}_x$  ECAs, allow 0.1 wt% S from 2015) and at global level (0.5 wt% S from 2020, possibly postponed to 2025), there is an interest to study how the lower sulfur content in marine fuels will affect particle emissions.

Knowledge about the size distribution of the emitted particles is important for assessments of impact on human health and fate in atmosphere. Fine particles (diameter, ( $D_p$ ) < 2.5  $\mu\text{m}$ ) reach deeper down in the respiratory system and ultrafine particles ( $D_p < 0.1 \mu\text{m}$ ) may be transported further to other parts of the body with the blood (Pope and Dockery, 2006). Other properties to consider are chemical composition, number concentration and

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mass (Finlaysson-Pitts and Pitts, 2000). Further, the volatility of the particles may be important, since it will impact the particles aging in the atmosphere (Salo et al., 2011).

Particles emitted from operating ships comprise of different compounds, e.g. particulate sulfate, black carbon (BC), ash and heavy metals associated to fuel and lubrication oil (Lack et al., 2009; Moldanová et al., 2009). Both fuel type and quality together with parameters related to the engine will have an impact on the character of the particle emissions (Lack et al., 2009). In aspect of particle size, solid particles from operating ships are found to peak at smaller particle sizes than particles from land-based sources, 20–40 nm and 50–100 nm respectively (Kasper et al., 2007). However, also particles with diameters of several  $\mu\text{m}$  have been observed in emissions from ship engines running on heavy fuel oil (HFO) (Fridell et al., 2008; Lyyränen et al., 1999). The nanoparticles ( $D_p < 50$  nm (Hinds, 1999)), are of primary and secondary origin. They consist of volatile sulfuric and organic compounds, together with compounds of solid carbon and metals, while larger particles ( $D_p > 50$  nm) are of solid character and consist of carbonaceous agglomerates with associated and absorbed species (Kittelson, 1998).

There are few studies that consider emissions of small particles, i.e. nanoparticles with respect to number concentration and size distribution, from ship engines operating at low loads e.g. manoeuvring and use low sulfur marine fuels for propulsion. Hallquist et al. (2013), Fu et al. (2013) and Moldanová et al. (2013) have performed onboard measurements that consider some of these areas. Petzold et al. (2011), Kasper et al. (2007), Ushakov et al. (2012, 2013) present results from measurements on different test-bed engines and focus on different loads and fuel types.

The aim of this study is to characterize the particle emissions from four different fuels, when the engine is operating at lower engine loads ( $\leq 35\%$ ). The fuels used were Swedish Environmental class 1 (MK1) and class 3 diesel (MK3) and HFO (0.12 wt% S) and marine diesel oil (MDO, 0.52 wt% S). MK1 and MK3 are similar with the fuels that are used for inland shipping, while MDO are used onboard ocean-going ships. The HFO used here has lower sulfur content than the HFO normally used on ocean-going ships today. However, the sulfur content complies with limits in future regulations in  $\text{SO}_x$  ECAs (0.10 wt% S 2015) and makes it possible to study the emissions from combustion of an HFO with low sulfur content and investigate what other properties of the fuel that affect the particle emissions. The sulfur content of the MDO is in line with up-coming regulation of allowed sulfur content in marine fuel oils at global level (0.5 wt% S 2020).

## 2. Method and experimental setup

### 2.1. Experimental setup

The measurements were conducted in a test-bed engine lab equipped with a 4-stroke, turbocharged Volvo Penta D3-110 marine diesel engine. The engine has five cylinders with a crankshaft power of 81 kW, maximum engine speed of 3000 rpm and is equipped with a common rail injection system. The engine is designed with four separate heated fuel tanks in order to control the viscosity of the fuel. During the experiments described here the maximum load and speed was restricted to 35% and 1750 rpm, respectively. The properties of the fuels and lubrication oils used during the two campaigns (Campaign 1 in March 2012 and Campaign 2 in October 2012) are presented in Table 1. Results for MK3 are from Campaign 1, while the other results are from Campaign 2. The HFO used here was diluted with 50% (by volume) MK1 to reduce the viscosity. According to the manufacturer, the injection system is optimized for fuels with a density of 810–860  $\text{kg}/\text{m}^3$  at 15 °C and viscosity of 1.5–4.5 cSt at 40 °C. The values for both viscosity and density for the

**Table 1**

Properties of the fuels (MK1, MK3, HFO and MDO) and lubrication oils (Lub. oil 1 from campaign 1 and Lub. oil 2 from campaign 2) used in Campaigns 1 and 2. n.a. stands for not analyzed.

	MK1	MK3	HFO	MDO	Lub. oil 1	Lub. oil 2
Aromatic content (v/v%)	4.4	15.4	7.7	18.1	n.a.	n.a.
Ash content (% m/m)	<0.010	<0.010	<0.020 <sup>a</sup>	n.a.	n.a.	n.a.
Carbon residue (% m/m)	<0.20	<0.20	<7.0 <sup>a</sup>	n.a.	n.a.	n.a.
Density at 15 °C ( $\text{kg m}^{-3}$ )	819.0	835.5	948.4 <sup>a</sup>	862.9	n.a.	n.a.
PAH content	<0.02 v/v%	2.3 m/m%	1.4 v/v%	3.3 v/v%	n.a.	n.a.
Viscosity (cSt)	2.093 <sup>b</sup>	2.595 <sup>b</sup>	3.6 <sup>c</sup>	<1–2.5 <sup>b</sup>	n.a.	n.a.
Sulfur (wt%)	<0.0003	0.0003	0.12	0.52	n.a.	n.a.
Vanadium ( $\text{mg kg}^{-1}$ )	<0.05	n.a.	1.10	<0.05	<1	1
Nickel ( $\text{mg kg}^{-1}$ )	<0.05	n.a.	1.10	<0.05	1	1
Iron ( $\text{mg kg}^{-1}$ )	0.05	n.a.	0.50	0.10	40	20
Calcium ( $\text{mg kg}^{-1}$ )	0.05	n.a.	0.30	0.05	2850	2400
Zinc ( $\text{mg kg}^{-1}$ )	n.a.	n.a.	0.10	0.40	1275	1150

<sup>a</sup> For HFO not diluted with MK1.

<sup>b</sup> Viscosity at 40 °C.

<sup>c</sup> Viscosity at 40 °C, measured with a Viscomar viscometer, MAR-TEC Marine GmbH.

studied fuels are in accordance with the limits set by the manufacturer.

The experimental set-up is illustrated in Fig. S1. Two types of aerosol instruments were used: an Engine Exhaust Particle Sizer (EEPS, Model 3090, TSI Inc.) measuring particles in the size range of 5.6–560 nm; and a Dust Monitor (Model 1.108, Grimm) measuring particles in the size range from 300 nm to over 20  $\mu\text{m}$  in diameter. The EEPS classifies the particles after their differential electrical mobility and the Grimm uses light scattering technology to count the number of particles and classify into different sizes (TSI, 2006; Grimm Aerosol Technik GmbH & Co KG, 2010). The instruments were measuring simultaneously and were connected directly to the dilution system (FPS, Model 4000, Dekati) and the raw exhaust was diluted in two steps. The primary dilution occurred in a perforated tube with preheated, clean and dry air (300–315 °C, i.e. the temperature of the raw exhaust gas). The secondary dilution used clean air of ambient temperature to dilute the sample and an ejector diluter drew the sample from the primary dilution section. According to the manufacturer the residence time in the system is below 0.5 s (Dekati, 2010). Table S1 presents data about the dilution ratios and dilution conditions during the measurements. To quantify the non-volatile fraction of emitted particles, i.e. primary solid particles, a thermodenuder (TD, Dekati), heated to 300 °C was used.

For most experiments, except for MK1 (all loads) and MDO (35% load), the FPS was connected to the exhaust gas pipe with a heated tube (held at 300–315 °C). For MK1 (all loads) and MDO (35% load) the FPS was connected directly on the exhaust gas pipe. The aerosol samples were extracted under isokinetic conditions using a fixed inlet (Apex instruments) adapted to the exhaust and sampling flows (Hinds, 1999). Additionally, samples on Teflon filters were collected at 35% engine load for each fuel type for subsequent gravimetric (total suspended particles (TSP)), BC and elemental analysis. The BC content was determined with a visible light reflectometer that is a part of the beta gauge monitor FH62 I–N (ESM Emberline, Germany) (Pettersson et al., 2011). For the elemental analysis Energy Dispersive X-Ray Fluorescence (EDXRF) was used (Boman, 2009).

During Campaign 2 gaseous compounds: nitrogen monoxide (NO), nitrogen oxides ( $\text{NO}_x$ ), sulfur dioxide ( $\text{SO}_2$ ), carbon monoxide

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